Kilo-hertz QPO in Island State of 4U1608-52 as Observed with RXTE/PCA

W. Yu[1], S. N. Zhang[2,3], B .A. Harmon[3], W. S. Paciesas[3,7], C. R. Robinson[2,3], J. E. Grindlay[4], P. Bloser[4], D. Barret[5], E. C. Ford[6], M. Tavani[6], P. Kaaret[6]

Received 9 July 1997; accepted 3 October 1997

[1]LCRHEA, Institute of High Energy Physics, Beijing 100039, China

[2] Universities Space Research Association, Huntsville, AL 35806

[3] NASA/Marshall Space Flight Center, ES-84, Huntsville, AL 35812

[4] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

[5] Centre d'Etude Spatiale des Rayonnements, CNRS-UPS, BP4346, 31028 Toulouse Cedex 04, France

[6]Columbia Astrophysics Laboratory, Columbia University, 538 West 120th Street, New York, NY 10027

[7] University of Alabama in Huntsville, Department of Physics, Huntsville, AL 35899

ABSTRACT

We report RXTE/PCA observations of 4U 1608-52 on March 15, 18 and 22 immediately after the outburst in early 1996. The persistent count rates ranged from 190 to 450 cps (1-60 keV). During this period of time, 4U 1608-52 was in the island state. We detected QPO features in the power density spectra (PDS) at 567-800 Hz on March 15 and 22, with source fractional root-mean-square (*rms*) amplitude of 13%-17% and widths of 78-180 Hz. The average *rms* amplitude of these QPO features is positively correlated with the energy. Our results imply that the neutron star spin frequency is possibly between 300 Hz and 365 Hz.

Subject headings: X-ray:stars — stars:individual(4U 1608-52) — stars: neutron

1. Introduction

4U1608-52 is a transient low-mass X-ray binary with outbursts which recur on timescales of 80 days to two years (Grindlay and Liller 1978; Lewin et al. 1993; Lochner et al. 1994). It was classified to be an atoll source based on the correlated X-ray spectral variability and high-frequency-noise (HFN) in the X-ray intensity (Hasinger & van der Klis 1989; Yoshida et al. 1993). 4U 1608-52 has been observed a few times with an energy spectrum consistent with a power-law at X-ray luminosities below 10^{37}ergs/s (Mitsuda et al. 1989; Penninx et al. 1989; Yoshida et al. 1993; Zhang, S.N. et al. 1996).

The X-ray monitoring of 4U1608-52 with RXTE/ASM indicated an outburst in early 1996. In response to a high state detection of 4U1608-52 in RXTE/PCA scans (Marshall and Angelini 1996), pointed observations with the RXTE/PCA were conducted during the decay phase of this outburst on March 3, 6, 9, and 12 (Berger et al. 1996; van der Klis 1997a), and on March 15, 18, and 22 (see Fig.1). Kilo-hertz QPOs were discovered in 4U 1608-52 in March 3, 6, and 9 observations. No X-ray bursts were observed with RXTE/PCA in early March 1996 (Berger et al. 1996). Here we report the timing analysis results on RXTE/PCA observations of 4U 1608-52 on March 15, 18, and 22.

2. Observations and Analysis Results

X-ray monitoring by RXTE/ASM shows that our observations on March 15, 18 and 22 were taken near the end of the outburst decay, with ASM daily-averaged brightness of 44.8$\pm$5.2, 13.3$\pm$7.2, and 14.5$\pm$4.1 mCrab respectively (see Fig.1). The persistent X-ray flux (2-20 keV) obtained with the RXTE/PCA was in the range between 4.6×10^{-10}erg/s/cm^2 and 1.1×10^{-9}erg/s/cm^2. The source count rate in the energy range 1-60 keV varied between 190 and 450 cps. Three X-ray bursts were observed in one orbit on March 22. They

show the evidence of a high energy excess above a Planckian spectrum, but no kilo-hertz QPO were detected in the bursts (Yu et al. 1997, in preparation). We thus exclude 50 seconds data of each burst when estimating the properties of the kilo-hertz features in the persistent emission.

The PCA/RXTE provides several data modes which were used in the analysis reported in this paper. The color-color diagrams were constructed from the *Standard 2 Mode* data, which provides 129 energy channels and 16 second time resolution. We made use of the *Event Mode* data (64 energy channels and 122 μs time resolution) to generate the power density spectra (PDS) from 0.001 Hz to 100 Hz.

2.1. Color-Color Diagrams

Background count rates as a function of time were produced with the standard background model supplied by the RXTE Guest Observer Facility (Stark et al. 1997). After subtracting the background in 3 bands (approximately 2.2-5.1, 5.1-10.1, and 10.1-29.8 keV), light curves and color-color diagrams for 4U1608-52 were generated. Fig.2 is the color-color diagram of 4U 1608-52 plotted with the data obtained on March 15, 18, and 22, as triangles, squares, and circles, respectively. Each data point represents 240s of observation. The data for about 2000s, starting from the rise of the first burst to the end of that orbit, were excluded. The uncertainty in the hardness ratios were also estimated for a hypothetical EXOSAT observation, as shown in Fig.2.

2.2. Power Density Spectra (PDS)

We have obtained rebinned PDS in the frequency range of $10^{-3} - 100$ Hz from background-subtracted light curve of the *Event Mode* data. The average PDS of individual

days on March 15, 18 and 22 are shown in Fig. 3. The average level of the white noise caused by counting statistics was subtracted in these spectra. These PDS show similar HFN components with a flat top from 0.01 Hz to about 10 Hz. The low frequency noise (LFN) can be represented by a power-law and the HFN components can be described as a power-law with an exponential cutoff for atoll sources (Hasinger & van der Klis 1989). This model basically agrees with our data as shown in Fig.3. The fractional *rms* of the HFN for each day is $12.0 \pm 1.9\%$, $13.5 \pm 1.6\%$, and $14.4 \pm 0.6\%$, respectively. The correponding HFN cut-off frequencies are 25 ± 6, 8 ± 2, and 19 ± 3 Hz. All the above errors represent a 90% confidence level (Press et al. 1992).

In the PDS of the first orbit on March 15, a QPO peak at 20 Hz can be seen. A broad excess of power at 10-30 Hz is also visible in the second and third orbits on March 15. Further analysis of the *Single-Bit Mode* data and the *Event Mode* data in each orbit at higher frequencies revealed QPO features in the frequency range of 567-800 Hz in the average PDS. An example of the Leahy-normalised PDS obtained from the *Event Mode* data in 1-30 keV in the 3rd orbit on March 15 is shown in Fig. 4. There is broad excess of power between a few tens Hz to about 200 Hz in each of the PDS on March 15 and 22. The results are listed in Table 1. All errors in the table correspond to unreduced $\Delta\chi^2 = 1$. We estimate the *rms* amplitudes of the kilo-hertz QPO peaks by fitting PDS at 200-2000 Hz range with a linear component plus a Lorentzian peak. The *rms* amplitudes of the QPO peaks were obtained from the Lorentzian component.

We then divided the 2-60 keV energy range into 7 bands (2.2-3.5 keV, 3.5-5.4 keV, 5.4-7.9 keV, 7.9-11.1 keV, 11.1-14.6 keV, 14.6-20.4 keV and above 20.4 keV) and studied the PDS in these bands using the *Event Mode* data. The QPO peaks were usually not clearly visible in the average PDS in each of the 7 bands. The individual PDS in the frequency range between 200 Hz and 2000 Hz were fit with a model composed of a linear component

plus a box function. The box functions were centered at the peak frequencies and widths were set to be 2 times of the QPO FWHMs (see Table 1). Then we calculated the *rms* amplitude from the box function integrals. Finally we averaged the *rms* amplitudes from each energy-dependent PDS over the six orbits. A positive correlation between the average QPO *rms* amplitude and the photon energy was observed, as shown in Fig.5.

We also notice that there is no apparent correlation between the QPO *rms* and the intensity. But the QPO centroid frequencies and the average source intensities show the tendency of a positive correlation within a few hours (see Fig.6). For example, on March 15, the higher the count rates, the higher the QPO frequencies were. On March 22, a similar trend was also observed.

3. Discussion

Kilo-hertz QPOs in X-ray flux have been observed from about twelve LMXBs so far (van der Klis 1997b and references therein; Zhang, W. et al. 1997). Nine of them are atoll sources or probable atoll sources. In our observation of 4U 1608-52, its persistent flux in the 2-20 keV band ranged between $(4.6-11)\times10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, corresponding to an X-ray luminosity of $(0.7-1.7)\times10^{36}\,\mathrm{erg\,s^{-1}}$ assuming a distance of 3.6 kpc (Nakamura et al. 1989). The luminosity was at or below the lowest luminosity of 4U 1608-52 in its island state ever observed with EXOSAT and Ginga (Penninx et al. 1989; Yoshida et al. 1993). We detected no large motion in the PCA color-color diagram within a day. Also, the power density spectra were dominated by HFN with *rms* around 13%. This suggests that 4U 1608-52 was in its island state (Hasinger & van der Klis 1989; van der Klis 1995). It is the second atoll source observed to exhibit kilo-hertz QPO in both the banana and the island state (the first is 4U 1636-53, see Wijnands et al. 1997).

The increase in QPO *rms* amplitude with photon energy in our observations shows that the QPO emission is harder than the average spectrum. A positive correlation between *rms* amplitude and photon energy in the range from 2 keV to more than 11 keV has also been observed from kilo-hertz QPOs in other sources (for example, Ford et al. 1997b and Zhang, W. et al. 1996). This suggests that all these QPOs are of similar origin.

Our QPO observations can be compared to the observations of 4U 1608-52 made in early March (Berger et al. 1996). In all observations only a single QPO with centriod frequency above 200 Hz has been detected and the QPO *rms* amplitude increases with photon energy. The *rms* amplitude versus energy curve for March 15 and 22 is consistent with that presented for March 3 (Berger et al. 1996). However, on March 3 and 6, the QPO was with a FWHM of 5–15 Hz in the PDS averaged over 100 seconds; while on March 9, 15, and 22, the QPO can not be tracked as the QPO observed on March 3 and 6, and was with a FWHM of 80–140 Hz, which are derived from the average PDS over a few thousand seconds. On March 3, the X-ray intensity was high and the QPO frequency varied in the range 830-890 Hz with no correlation with X-ray intensity (Berger et al. 1996). Comparing individual orbits on March 15 and 22, when the X-ray intensity is lower, the QPO frequency is lower (570–800 Hz) and appears to be positively correlated with X-ray intensity. This correlation does not hold when data from different days are compared. A similar trend of correlation over one day time scales and lack of correlation on longer timescales has been observed for QPO frequency versus X-ray intensity in other X-ray burster sources (Ford et al. 1997a; Zhang, W. et al. 1997). However, the correlation of QPO frequency with the flux of a blackbody component of the X-ray spectrum was found to be robust over several months in 4U 0614+091 (Ford et al. 1997b).

Kaaret et al. (1997) have interpreted the lack of correlation between QPO frequency and X-ray intensity of 4U 1608-52 on March 3 as reported in Berger et al. (1996) as evidence

that the accretion disk is terminated near the marginally stable orbit when the source is at high X-ray intensities and high mass accretion rates. The March 15 and 22 observations presented here suggest that the QPO frequency may be correlated with X-ray intensity, at least over one day time scales, when 4U 1608-52 is at low X-ray intensities. This is consistent with the interpretation of Kaaret et al. (1997) since, when the mass accretion rate is low, the disk should be disrupted by the neutron star magnetosphere or radiation forces outside the marginally stable orbit and the QPO frequency should then be correlated with mass accretion rate (Alpar & Shaham 1985; Miller et al. 1997). It is important that additional observations of 4U 1608-52 be obtained over a wide range of X-ray intensities.

It is also possible that the QPOs observed on March 15 and 22 may correspond to a pair of QPOs, but only one of the two is detectable in the individual orbit (see Fig.6). This would imply that the frequency separation is larger than 233$\pm$22 Hz (Fig.6). It is thus reasonable to assume that the neutron spin frequency is larger than 233 Hz, within the framework of the beat frequency model discussed above. If we interpret the 20 Hz QPO observed on March 15 as due to the Lense-Thirring precession in the model of Stella and Vietri (1997), the inferred neutron star spin frequency for 4U 1608-52 is between 300 Hz and 365 Hz, depending on the tilt angle off the equatorial plane. However, future simultaneous detection of all three QPOs (the Lense-Thirring precession frequency, the beat frequency and the Kerplerian frequency, as of 20 Hz, 435-500 Hz and 800 Hz respectively in the case of March 15 observation) in 4U1608-52 or a detection of QPO in the X-ray bursts from 4U 1608-52 is needed to confirm the above inference.

We appreciate the assistance of RXTE/GOF in data reduction and analysis and Dr. S. Dieters of UAH for help with the RXTE data analysis software and various suggestions. WY would like to acknowledge partial support from the National Natural Science Foundation of China.

REFERENCES

Alpar, A. and Shaham, J. 1985, Nature, 316, 239

Berger, M., et al. 1996, ApJ, 469, L13

Ford, E. et al. 1996, ApJ, 475, L123

Ford, E. et al. 1997b, ApJ, 486, L47

Ghosh, P., and Lamb, F.K. , in X-ray Binaries and Recycled Pulsars, eds. E.P.J. Van den Heuvel & S.A. Rappaport, P.487-510, Kluwer Academic, Netherlands (1992)

Grindlay, J.E., and Liller, W. 1978, ApJ, 220, L127

Hasinger, G., van der Klis, M. 1989, A&A, 225, 79

Kaaret, P., Ford, E.C., and Chen, K. 1997, ApJ, 480, L27

Lewin, W.H.G, van Paradijs, J., and Taam, R.E. 1993, Space Sci. Rev., 62, 223

Lochner, J.C., Roussel-Dupré, D. 1994, ApJ, 435, 840

Marshall, F.E., Angelini, L. 1996, IAU Circ.6331

Miller, M.C., Lamb, F.K., and Psaltis, D. 1996, submitted to ApJ

Mitsuda, K., Inoue, H., Nakamura, N., and Tanaka, Y. 1989, PASJ, 41, 97

Nakamura, N. et al. 1989, PASJ, 41, 617

Penninx, W. et al. 1989, A&A, 208, 146

Press, W. H., et al. , in Numerical Recipes in Fortran : the Art of Scientific Computing, P.684-694, Cambridge University Press (1992)

Stark, M., and the XTE/PCA team, http://lheawww.gsfc.nasa.gov/docs/xte/pcabackest.html/, 1997

Stella, L. & Vietri, M. 1997, ApJ, in press (astro-ph/9709085)

van der Klis, M. 1995, in X-Ray Binaries, ed. W.H.G.Lewin, J. van Paradijs, and E.P.J.van den Heuvel (Cambridge: Cambridge Univ. Press), 277

van der Klis, M. private communication, 1997a.

van der Klis, M., to be published in the Proceedings of the Wise Observatory 25th Anniversary Symposium "Astronomical Time Series", 1997b (astro-ph/9704272).

Wijnands, R.A.D. et al. 1997 ApJ, 479, L141

Yoshida, K., et al. 1993, PASJ, 45, 605

Zhang, W., Lapidus, I., White, N.E., and Titarchuk, L. 1996, ApJ, 469, L17

Zhang, W. et al., 1997, in preparation

Zhang, S.N. et al. 1996, A&AS, 120, 279

This manuscript was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— Long-term X-ray monitoring of 4U 1608-52 by RXTE/ASM. Our observations with RXTE were on March 15, 18, and 22.

Fig. 2.— Color-color diagram of 4U 1608-52. Data from March 15, 18 and 22 pointings are plotted as triangles, squares, and circles, respectively. Each point represent a 240s of observation. The three data points on the left side of the plot show typical error bars for a hypothetical EXOSAT ME observation of 4U 1608-52 on the three days with the same energy bands used in the PCA and the computed ratio of the effective areas of the two instruments. On March 18, no significant kilo-hertz QPO is detected.

Fig. 3.— Average PDS on March 15, 18 and 22 obtained from the background-subtracted *Event Mode* data. The average level of the white noise caused by counting statistics was subtracted. The fits of the PDS with the model described in Hasinger and van der Klis (1989) are also shown in the plot, with reduced χ^2s (38 degrees of freedom) of 1.80, 1.84 and 1.08 respectively. The rms of HFN was about 13% in the above PDS.

Fig. 4.— Average Power Density Spectrum in the third orbit on March 15 obtained from the 1-30 keV *Event Mode* data. High frequency noise (HFN) is also visible below 100 Hz. We fit the PDS in 200-2000 Hz range with a model (solid curve) composed of a linear component plus a Lorentzian peak at 744 Hz.

Fig. 5.— Average fractional *rms* amplitude of QPO as a function of photon energy. We average the results obtained from *Event Mode* data analysis of the 6 orbits.

Fig. 6.— Average count rates (1-60 keV) vs. QPO frequency in 4U 1608-52 during the low state observation. Data points on March 15 and 22 were marked as squares and circles. No QPO peaks were observed on March 18.

Table 1. March 1996 RXTE Observations of 4U 1608-52[a]

Orbit Start Time[g]	Duration (s)	Count Rate[b] (cps)	Count Rate[c] (cps)	ν_{qpo}[d] (Hz)	FWHM[e] (Hz)	rms[f] (%)
March 3			2910-3400	830-890	5-15	$\sim 6-8$
March 6			1920-2500	830-870	5-15	~ 14
March 9			610-730	$691\pm^{6}_{6}$	$131\pm^{19}_{19}$	~ 13.9
March 12			460-710			
March 15 19:28	1800	300-350	150-180	$800\pm^{9}_{10}$	$78\pm^{25}_{20}$	$13.3\pm^{3.1}_{3.4}$
March 15 21:39	1200	300-340	155-185			
March 15 22:49	2700	280-330	150-175	$744\pm^{12}_{12}$	$116\pm^{40}_{30}$	$14.4\pm^{3.3}_{3.7}$
March 18 19:46	2400	185-225	105-135			
March 18 21:10	3000	190-230	105-135			
March 22 15:11	1600	415-450	210-250			
March 22 16:14[h]	3600	415-450	210-240	$638\pm^{11}_{11}$	$126\pm^{25}_{32}$	$15.9\pm^{2.9}_{3.1}$
March 22 17:50	3600	375-430	200-230	$637\pm^{16}_{17}$	$173\pm^{53}_{41}$	$17.3\pm^{3.8}_{3.9}$
March 22 19:35	3000	370-430	190-240	$622\pm^{31}_{29}$	$180\pm^{123}_{100}$	$13.6\pm^{5.8}_{8.2}$
March 22 21:22	2400	370-415	190-230	$567\pm^{21}_{18}$	$134\pm^{93}_{82}$	$14.0\pm^{6.3}_{9.3}$
March 22 23:04	1400	345-415	184-230			

[a]Results before March 15 are from Berger et al. 1996 and the corresponding count rates are from van der Klis 1997a.

[b]The count rates in our observations were obtained from 1-60 keV light curve with 16s time resolution. The count rates obtained from 3 PCUs on March 22 have been rescaled to count rates as observed from 5 PCUs.

[c]The count rates in our observations were obtained from 5-60 keV light curve with 16s time resolution and rescaled as from 5 PCUs.

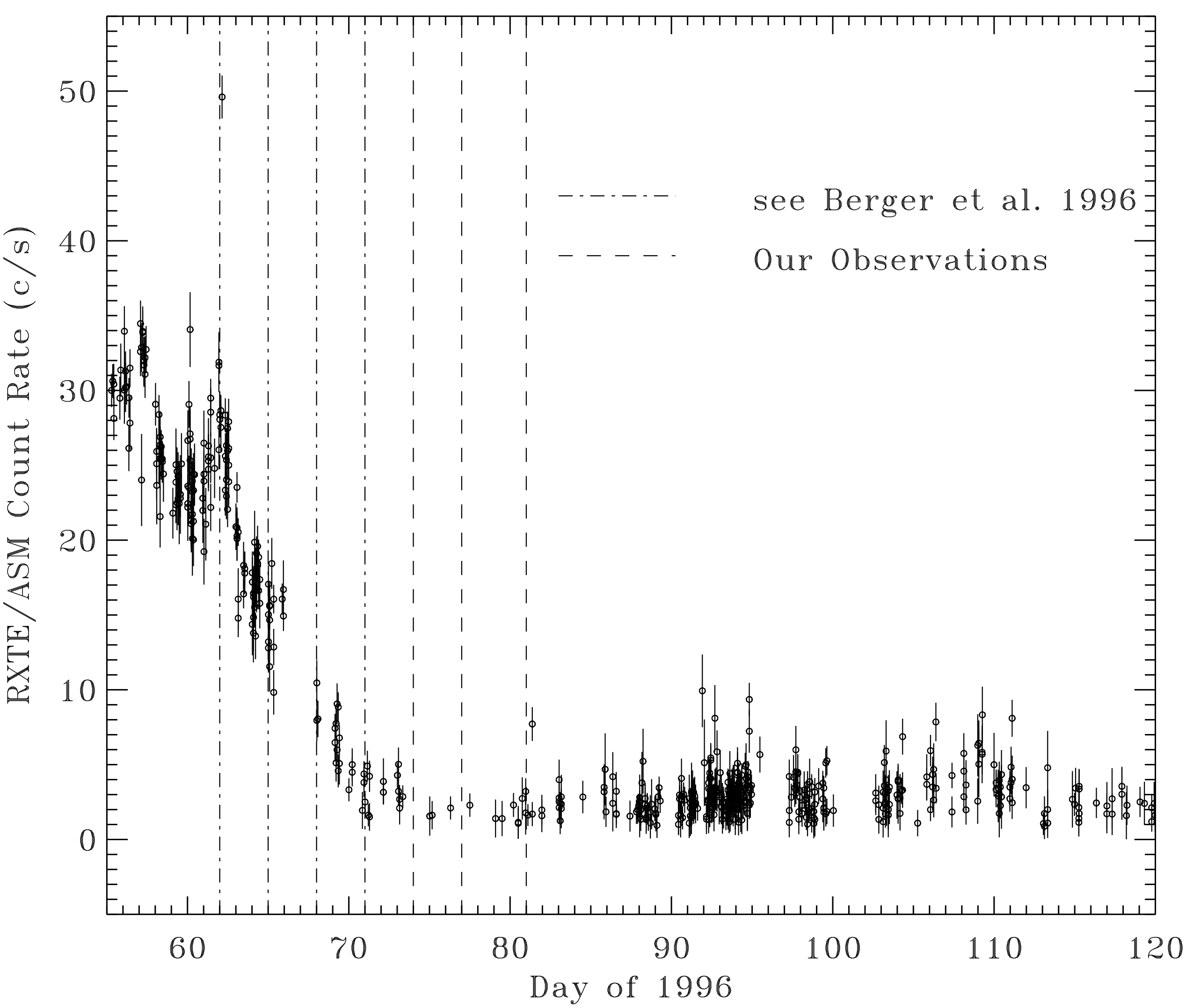
[d]The QPO centroid frequencies were obtained by fitting the peak with a Lorentzian.

[e]The FWHM of the Lorentzian peak in PDS.

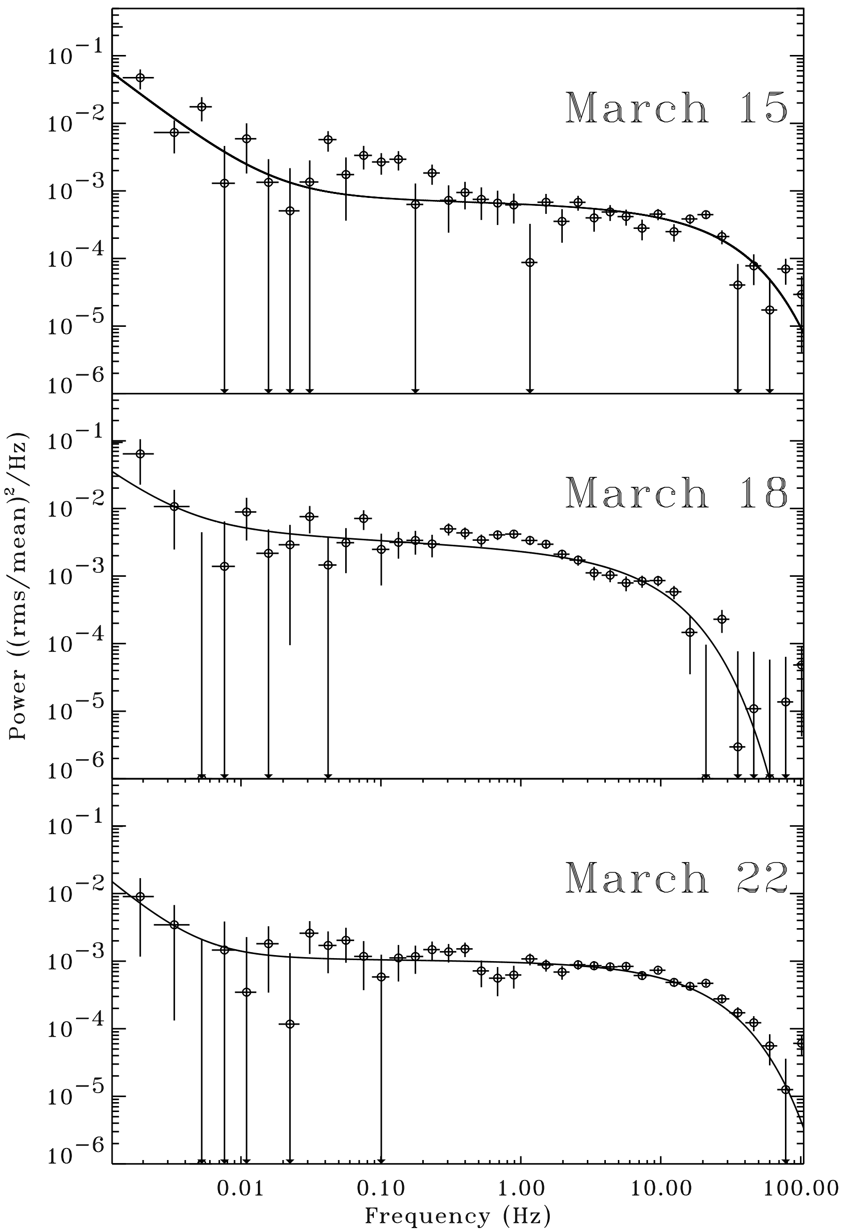
[f]All has been corrected to fractional *rms* amplitude of source intensity in 1-30 keV in our observation. Correction of binning effect has been applied.

[g]Start time (UT) of each orbit (date,hour:minute).

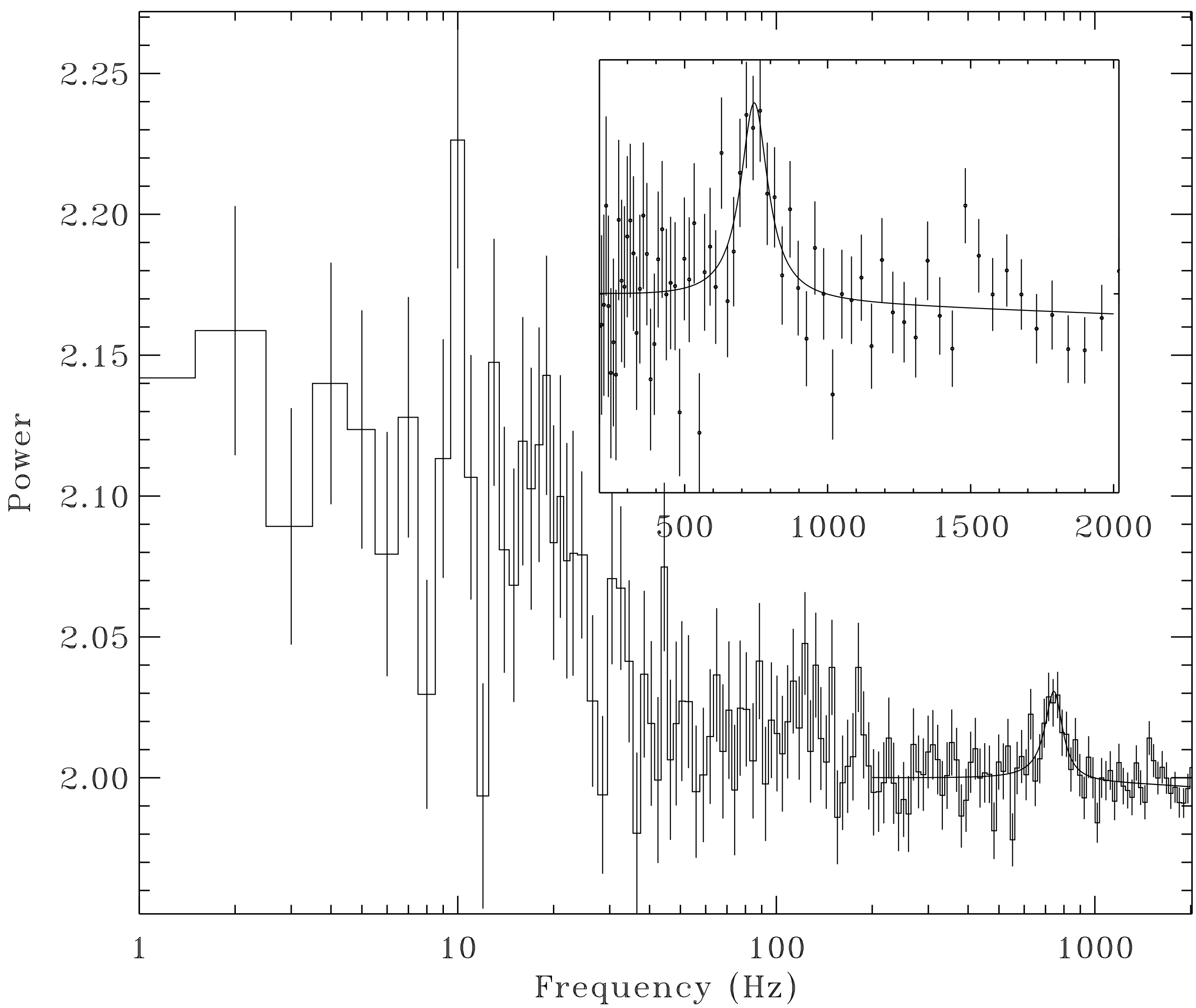
[h]We exclude 50s data of each burst to calculate the PDS in the orbit.



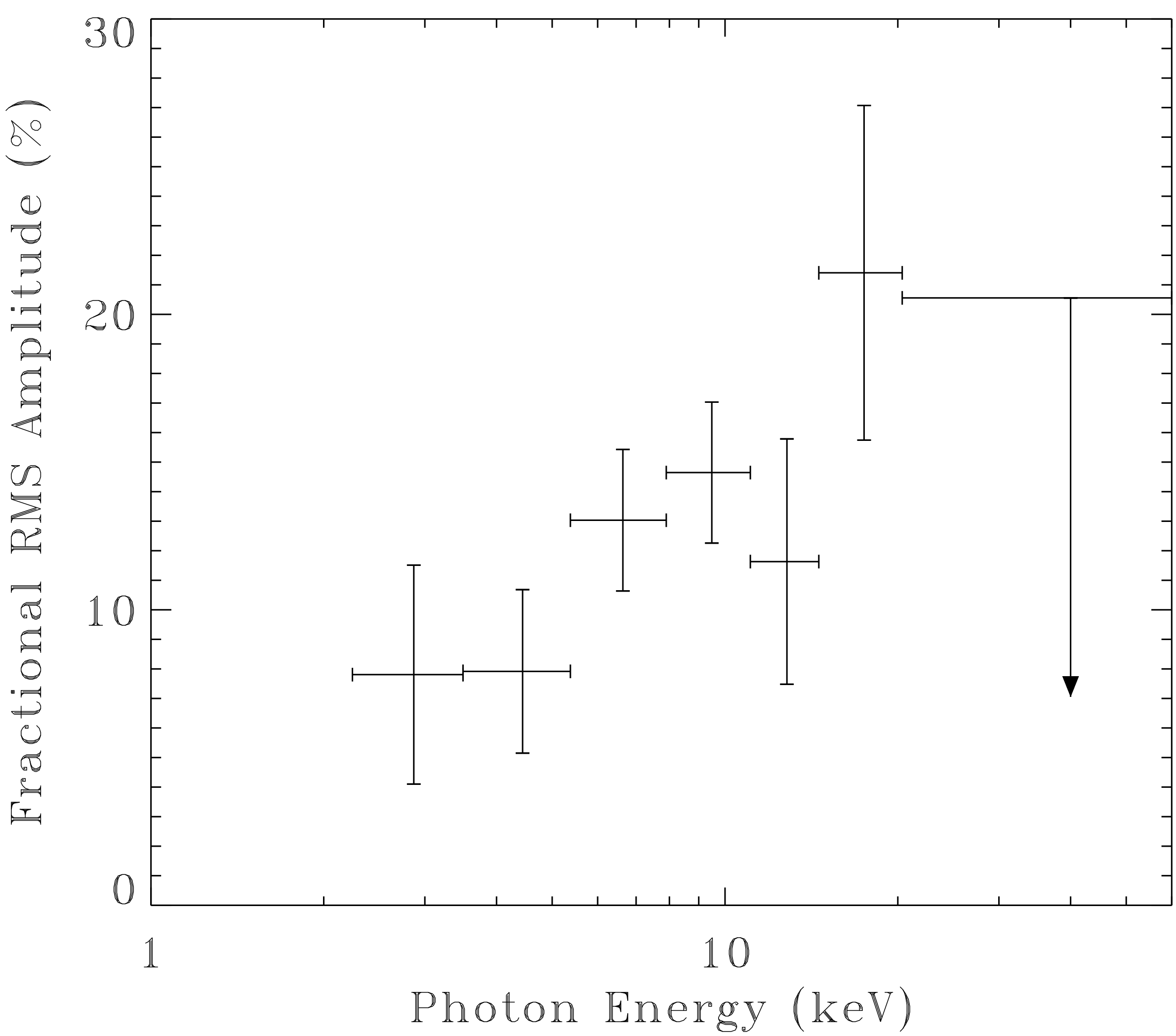
see Berger et al. 1996
Our Observations
RXTE/ASM Count Rate (c/s)
Day of 1996
0
10
20
30
40
50
60
70
80
90
100
110
120



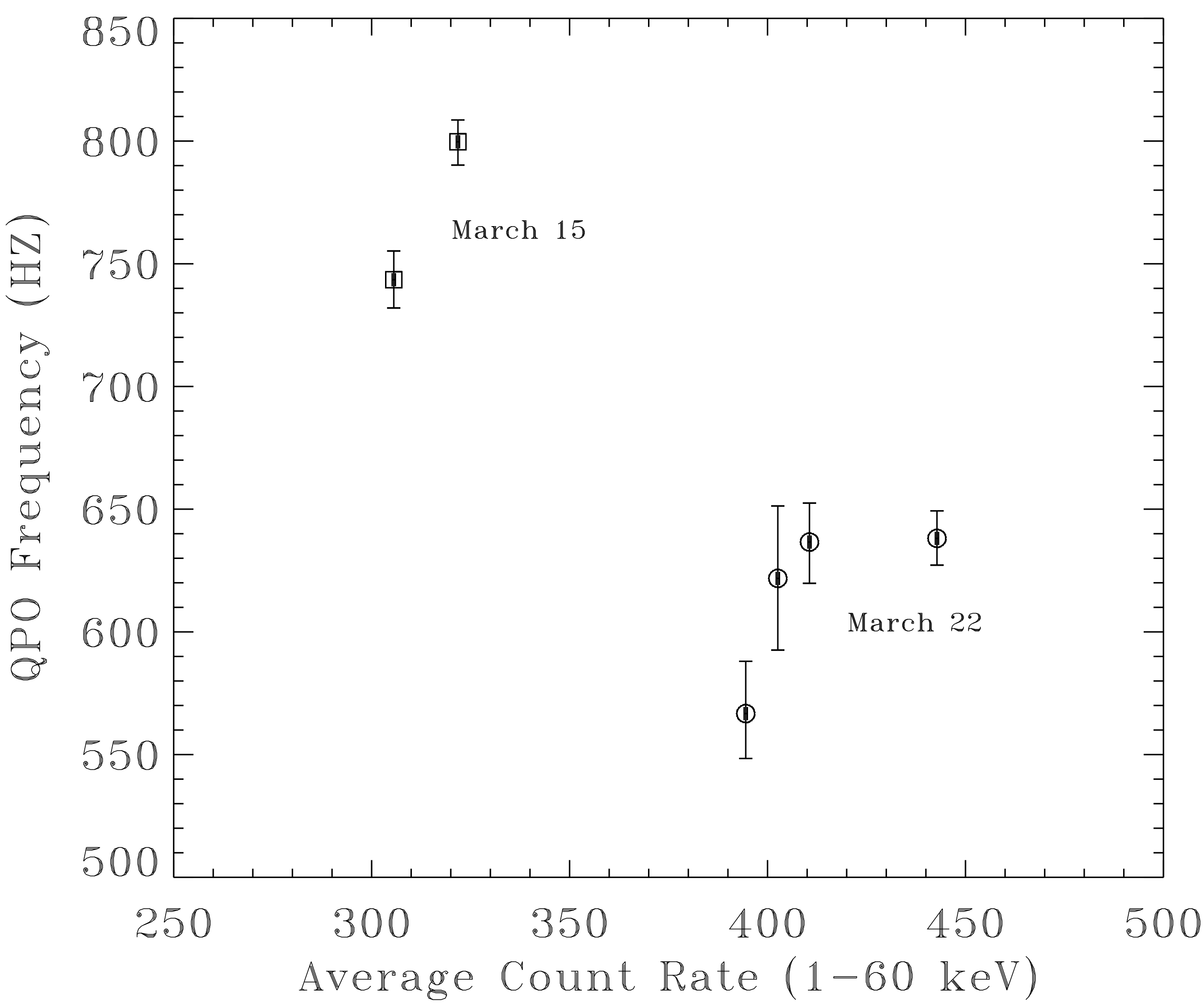
March 15
March 18
March 22
Power ((rms/mean)^2/Hz)
Frequency (Hz)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.01
0.10
1.00
10.00
100.00



2.25
2.20
2.15
2.10
2.05
2.00
Power
1
10
100
1000
Frequency (Hz)
500
1000
1500
2000



30
20
10
0
1
10
Fractional RMS Amplitude (%)
Photon Energy (keV)



850
800
750
700
650
600
550
500
250
300
350
400
450
500
QPO Frequency (HZ)
Average Count Rate (1-60 keV)
March 15
March 22